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RANGE DISTRIBUTION OF THE CHARGED PARTICLES FROM THE D-D REACTIONS FOR 10-MEV DEUTERONS: DIFFERENTIAL ELASTIC SCATTERING CROSS SECTION AT 40 DEGREES, 60 DEGREES, AND 80 DEGREES IN THE CENTER OF MASS SYSTEM

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FOR 10-MEV DEUTERONS:

DIFFERENTIAL ELASTIC SCATTERING CROSS SECTION AT 40 DEGREES, 60 DEGREES,

AND 80 DEGREES IN THE CENTER OF MASS SYSTEM

By Louis Rosen, Francis K. Tallmadge, and John H. Williams*

ABSTRACT

Microphotographic techniques have been used to obtain the range distribution of the charged particles resulting from the D-D reactions at center of mass angles of 40 degrees, 60 degrees, and 80 degrees for 10-Mev deuterons. At 80 degrees all of the groups of charged particles from these reactions are clearly resolved. The differential D-D elastic scattering cross sections have been obtained for the same angles and for these angles the cross sections per unit solid angle in the center of mass system are in the ratios of 1.00: 0.51: 0.42, respectively.

* * * * *

Photographic plate detectors were utilized to obtain the range distribution of the charged particles resulting from the D-D reactions and also to make absolute determinations of the D-D elastic scattering cross section at angles of 20 degrees, 30 degrees, and 40 degrees with respect to the incident beam in the laboratory system for 10-Mev deuterons from the Los Alamos cyclotron. The general instrumentation for this paper is the same as that described in a forthcoming paper by Curtis, Fowler, and Rosen entitled "Instrumentation for Nuclear Studies with Externally Focused Deutron Beam from 10-Mev Cyclotron." The experimental arrangement is given in Figures 1 and 2. The experiment consisted of bombarding thin gas targets with 10-Mev deutrons and simultaneously recording on photographic plates the number and ranges of the disintegration particles and scattered deuterons emitted into a known solid angle in a given direction.

Deuterium gas of 99.6 per cent purity at an accurately determined pressure in the region of 20 cm mercury was contained in the gas targets by thin mica windows—beam entrance and exit windows, and one window on each side of the target for the emergence of the scattered deuterons at the desired angle (in the case of the 40-degree target only one such window was used for the emergence of the scattered particles). The beam,

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focused at approximately the center of the gas target, was diaphragmed to a diameter of one-fourth inch immediately in front of the target. By using additional slits, the beam was defined to an angular divergence of 1.2 degrees in the horizontal direction and 0.85 degree in the vertical direction. Coulomb scattering by the entrance target windows never caused more than 2.5 per cent of the incident deuterons to be scattered through an angle greater than 1.0 degree. The deuteron current which passed through the target was collected in a 9 inch long Faraday cage and integrated with an electronic current integrator.

Three different gas targets were used, one for each of the angles investigated, the scattered deuterons being simultaneously recorded by two cameras, one on each side of the target, with the exception of the 40-degree target for which only one camera was used. Each camera contained a 100-micron Ilford C-2 plate which was prevented from seeing the beam by a thin aluminum window at the front of the camera. The plates made angles of approximately 7 degrees with the axes of the slit systems.

The cameras were set at accurately determined angles with respect to a 0-180-degree line, which line corresponded to the axis of the beam direction to within 0.3 degree. The angular resolution of the camera-target slit system geometry (Figure 2) was $\pm$ 0.45 degree for the 30-degree target, $\pm$ 0.70 degree for the 20-degree target and $\pm$ 0.36 degree for the 40-degree target. When the scattered deuterons were simultaneously recorded on each side of the target, as was the case for the 20-degree and 30-degree targets, both the energy and the direction of the beam were determined from the mean ranges of the deuteron groups. By using the range-energy relations given by Lattes, Fowler, and Cuer[1] and making allowance for the loss in range which the particles suffer in traversing the target window, target gas, and camera window the average energy of the beam prevailing during all the exposure was calculated to be 10.0 Mev $\pm$ 0.3 Mev at the center of the gas targets.

The calculation of the direction of the beam which prevailed during the exposures accurately determine the mean scattered deuteron ranges at two angles with respect to the incident beam (see Figure 6). These determinations were made by the same observer using the same equipment, and two sets of tracks having been recorded on plates which came from the same box. Under such conditions the ratio of the mean ranges could be determined to an accuracy of $\pm$ 1.5 per cent. It should be pointed out that it is necessary to know neither the absolute ranges nor the absolute value of the energy in order to accurately determine the beam direction from this method, for from Figure 2:

$$R_1\ (\theta) = K_1 E_o \operatorname{Cos}^2 \theta ,$$

$$R_2\ (\phi - \theta) = K_2 E_o \operatorname{Cos}^2 (\phi - \theta),$$

and

$$R_1/R_2 = K_1/K_2 \times \frac{\operatorname{Cos}^2 (\theta)}{\operatorname{Cos}^2 (\phi - \theta)} \qquad (1)$$

where E_o = incident deuteron energy at center of target, R_1 and R_2 are the ranges of the deuterons at their respective angles, corrected for the absorbers between the center of the target and the photographic plate, and

K_1/K_2 is determined from the range-energy relations.[1] The direction of the beam determined in this manner for the 30-degree point was calculated to be accurate to $\pm$ 0.25 degree. The beam maintained this direction during the 20-degree exposures and was, therefore, assumed to have this same direction during the 40-degree exposures.

The experimental procedure for making the range and cross section measurements was quite simple and straightforward. It consisted of lining up the cameras with respect to the center of the target and axis of the beam, pumping down the vacuum chamber, Figure 2, and then turning on the cyclotron with the focus magnet off, thus preventing the beam from reaching the scattering chamber during the "warm-up" period. When a steady external beam of the proper magnitude was obtained, the focus magnet was turned on and a beam of approximately 0.2 microampere was permitted to pass through the target. With such a beam an exposure of 1 to 3 minutes gave ample track density in our geometry.

The gas temperature in the target was taken to be the same as the temperature of the water cooling the target. Since the cyclotron was on for a very short time this temperature never changed measurably during an exposure.

Since many particles besides elastically scattered deuterons are produced when high energy deuterons impinge upon a deuterium target—protons and tritons from the reaction $D + D \rightarrow H^3 + H^1$, He^3 particles from the $D + D \rightarrow He^3 + n$ reaction and protons from the disintegration of the deuteron ($Q = -2.2$ Mev), it was thought desirable, in order to accurately determine the D-D scattering cross section, to make range analyses of the charged particles which come off at each of the angles investigated. Only tracks starting on the surface of the emulsion and traveling in the proper direction were included in this range analysis, thus effectively eliminating all background due to neutrons as well as all charged particle background which did not originate inside the target. It was necessary to eliminate about 2 per cent of the tracks which started on the surface of the emulsion because they did not travel in the proper direction. These tracks were caused by particles which either did not originate inside the gas target or else suffered scattering by the slit systems. In either case the tracks due to such particles were justifiably eliminated. The probability of the change of direction of scattered deuterons by coulomb scattering in the target and camera windows and in the target gas to such an extent that they would not be counted was calculated to be completely negligible. Figures 3, 4, and 5 give the results of range analyses at laboratory angles of 40.3 degrees, 30.0 degrees, and 20.1 degrees with respect to the incident beam direction. All of the charged particle groups from the D-D reactions are seen to be clearly resolved at 40 degrees. At 20 degrees the triton peak cannot at all be resolved from the deuteron peak, for at this angle the mean ranges of the two groups of particles differ by only 2.5 per cent. It should be pointed out that some of the tracks in the region of low range were undoubtedly caused by the scattering of deuterons from the walls of the target. Others of these low energy range tracks were, however, probably caused by protons arising from deuteron disintegration. The various groups are labeled with the particles

producing them and with their calculated residual ranges* in the emulsion. The energy widths at half maximum of the deuteron peaks are approximately 3 per cent which is quite close to what one expects from the geometry in these experiments. The resolution, therefore, appears to be much superior to what one might expect from counters in a comparable energy region. From such a range analysis it is a simple matter to determine with rather high precision the total number of tracks which are due to elastically scattered deuterons. (At 20 degrees a 2 per cent correction was applied for the tritons which were counted in the deuteron peak.) Having made such a determination, the procedure was adopted of counting all tracks originating in a swath of accurately known width, again counting only tracks which originated on the surface of the emulsion and proceeded in the proper direction. The charged particles coming from the target were collimated by two slits of accurately known dimensions, which slits were sufficiently narrow so that all the tracks in a swath were clustered approximately at the center of the plate.

In order to make an absolute cross section determination it was necessary to accurately determine the following: (1) the number of tracks per swath, width of swath, diameter of slits and their relative geometry with respect to the center of the plate and the center of the target, (2) the number of gas atoms per unit volume, and (3) the angle of the axis of the slit system with respect to the incident deuteron beam and the integrated beam current. The equation giving the absolute cross sections in terms of the foregoing considerations was developed by Dr. C. L. Critchfield. The geometrical factors which enter into this equation for the 30-degree points are illustrated in Figure 6. The equation is as follows:

$$Y = N\,I\,\sigma\,(\theta)\,n_o \tag{2}$$

$$I = \frac{4\,abw}{Ll\sin\theta}\left\{1 - \frac{a^2+b^2}{2l^2} - \frac{Pa^2+b^2\cot\alpha}{3l^2} + \frac{P^2\,a^2+Q^2\,b^2}{3l^2}\right\} \tag{3}$$

$$P = \frac{m\;[\cot\alpha - \cot\theta]}{L}$$

$$Q = \frac{(m+1)\;[\cot\alpha - \cot\theta]}{L}$$

Y = number of tracks appearing on a swath of width w.
N = number of incident beam particles that passed through the target.
n_o = number of scattering centers per unit volume.
$\sigma\,(\theta)$ = differential cross section in laboratory system.

By diaphragming the scattered particles so that they are concentrated about the center of the plate, the necessity for making accurate measurements of the angle that the surface of the emulsion makes with the direction of the scattered deuterons was eliminated.

* Range which particle has left after passing through the absorbing materials in its path on the way to the detector—D^2 gas, mica window in target, and aluminum window in camera.

This technique also essentially eliminated errors due to surface irregularities in the emulsion.

The errors in the measurements which enter into the cross section determination (equation 2) were determined to be as follows:

Quantity	Error (%)
Y	±3.5
ab	±1.5
w	±1.0
L	±2.0
θ	±1.0
n_o	±0.5
N	±3.5

Since the first term in the expansion for I (equation 3) determines approximately 99.5 per cent of this quantity for our geometries, the remaining terms need not be considered as far as errors are concerned. It is, therefore, seen that the RMS of all the above errors, which enter linearly into our cross-section determination is approximately ±5.5 per cent.

The D^2 gas used was specified as 99.6 per cent pure by the manufacturer. As a check on the purity with respect to heavy atoms (i.e., O_2 and N_2), it should be pointed out that in Figure 5 deuterons scattered by such atoms would have formed a peak at 328 ± 7 microns and deuterons scattered by protons would have formed a peak at 193 ± 4 microns. It is, therefore, seen that the number of tracks due to scattering from heavy nuclei for which the coulomb scattering cross sections would be many times the D-D cross section (the coulomb scattering cross section for O_2, for example, being 14.5×10^{-24} cm^2) indicates that the total amount of impurities in the D^2 gas from heavy elements is completely negligible. For D-P scattering, on the other hand, the cross section at 20 degrees is probably about one-third the D-D cross section. If this be so, it would indicate a maximum hydrogen impurity of less than 1 per cent, in good agreement with the manufacturer's specifications.

Several of the plates were analyzed by two observers using different microscopes and calibration equipment. It was a gratifying verification of the method to find that the number of tracks recorded per unit swath width always agreed to within the statistical accuracy of the determinations.

The results for the D-D scattering cross sections are given in Table 1. Figure 7 gives the differential cross section values as a function of angle in the center of mass system and also the differential cross sections for coulomb scattering as a function of angle in the same coordinate system. The differential cross section points appear to fall on a curve similar to the one obtained by Guggenheimer, Heitler, and Powell[2] for 6.5-Mev deuterons.

Table 1. D-D scattering cross sections per unit solid angle in the laboratory and center of mass coordinate systems.

θ (Lab)	$\sigma(\theta)$ (cm^2)	ϕ (C.M.)	$\sigma(\phi)$ (cm^2)
$40.3^\circ \pm 0.25^\circ$	$0.324 \pm 0.020 \times 10^{-24}$	$80.6^\circ \pm 0.4^\circ$	$0.106 \pm 0.006 \times 10^{-24}$
$30.0^\circ \pm 0.25^\circ$	$0.444 \pm 0.027 \times 10^{-24}$	$60.0^\circ \pm 0.4^\circ$	$0.128 \pm 0.008 \times 10^{-24}$
$29.5^\circ \pm 0.25^\circ$	$0.450 \pm 0.027 \times 10^{-24}$	$59.0^\circ \pm 0.4^\circ$	$0.131 \pm 0.008 \times 10^{-24}$
$20.1^\circ \pm 0.25^\circ$	$0.955 \pm 0.055 \times 10^{-24}$	$40.2^\circ \pm 0.4^\circ$	$0.254 \pm 0.015 \times 10^{-24}$
$19.7^\circ \pm 0.25^\circ$	$0.960 \pm 0.060 \times 10^{-24}$	$39.4^\circ \pm 0.4^\circ$	$0.255 \pm 0.016 \times 10^{-24}$

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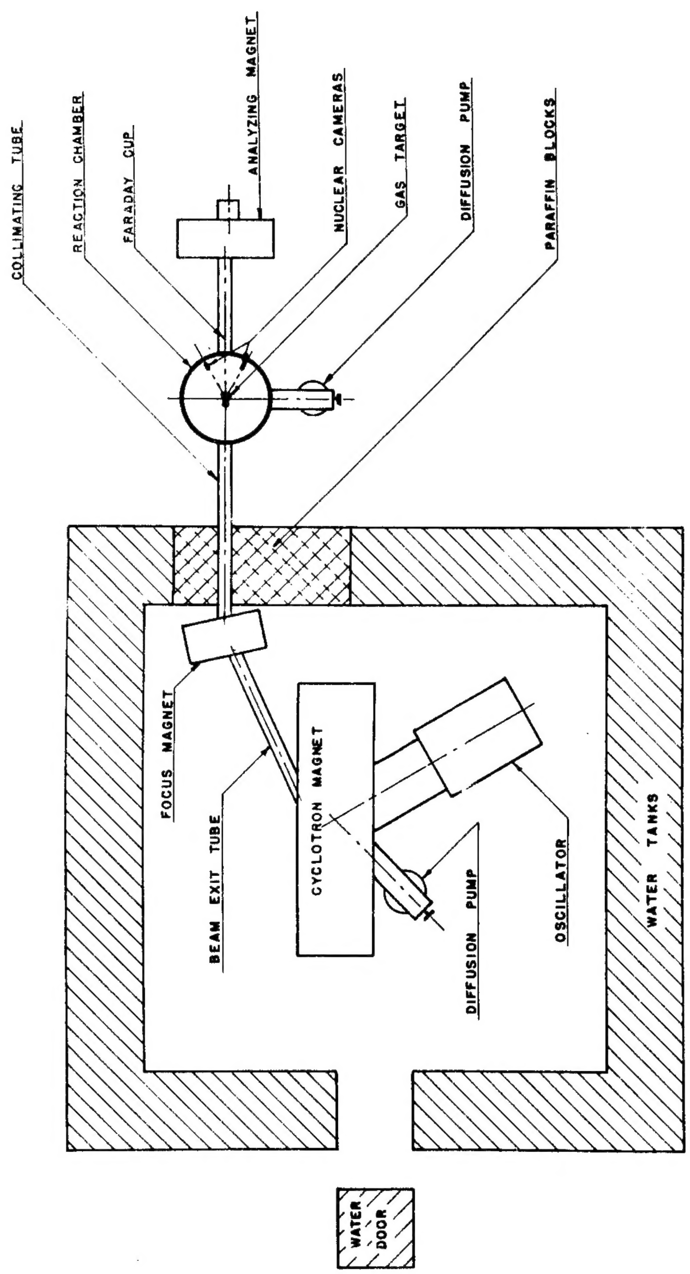
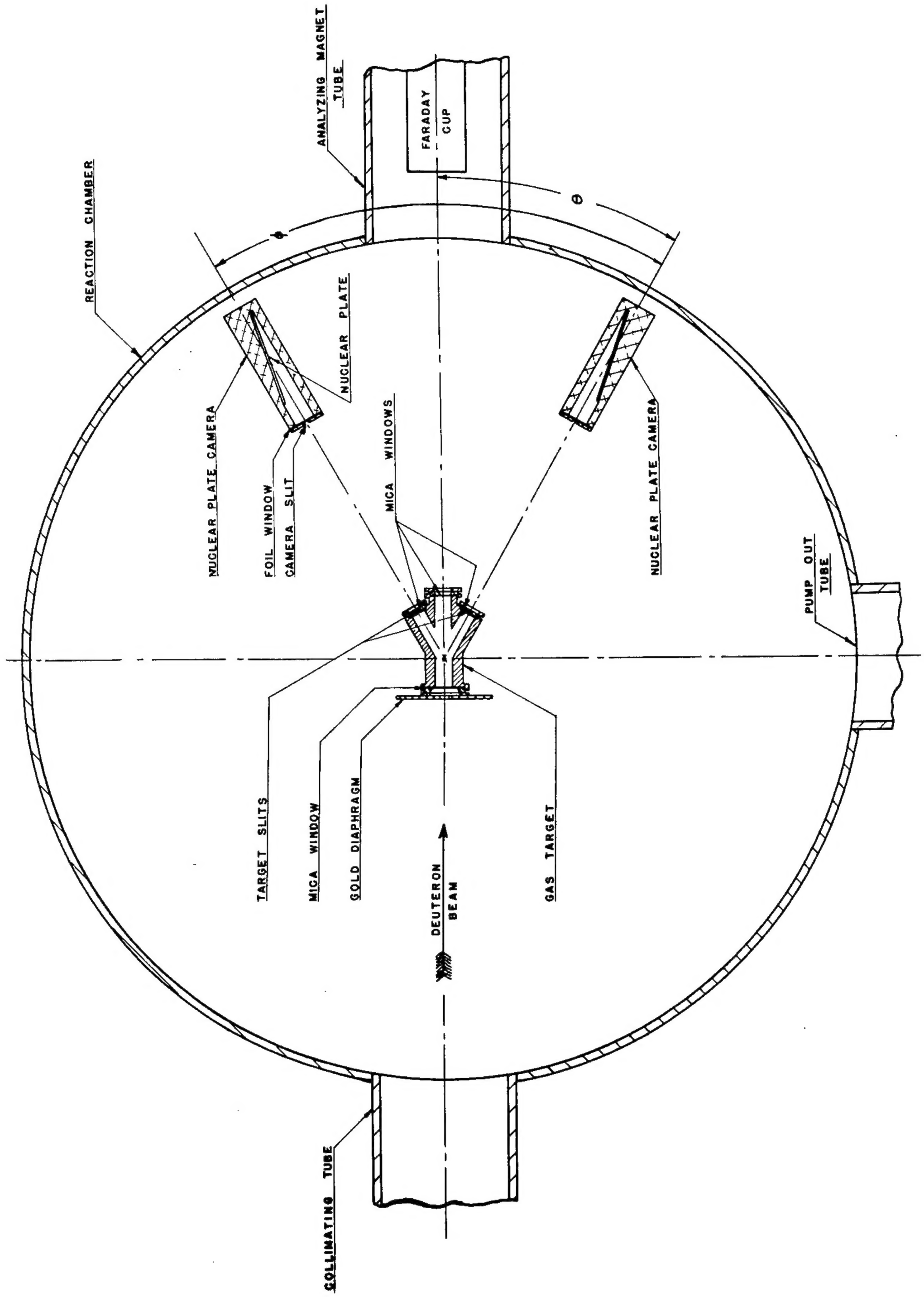
REFERENCES.

1. Lattes, Fowler, and Cuer, Nature 159:301 (1947).
2. Guggenheimer, Heitler, and Powel, Proc. Roy. Soc. 190:196 (1947).



EXPERIMENTAL LAYOUT

FIG. I



ENLARGED REACTION CHAMBER
FIG. 2

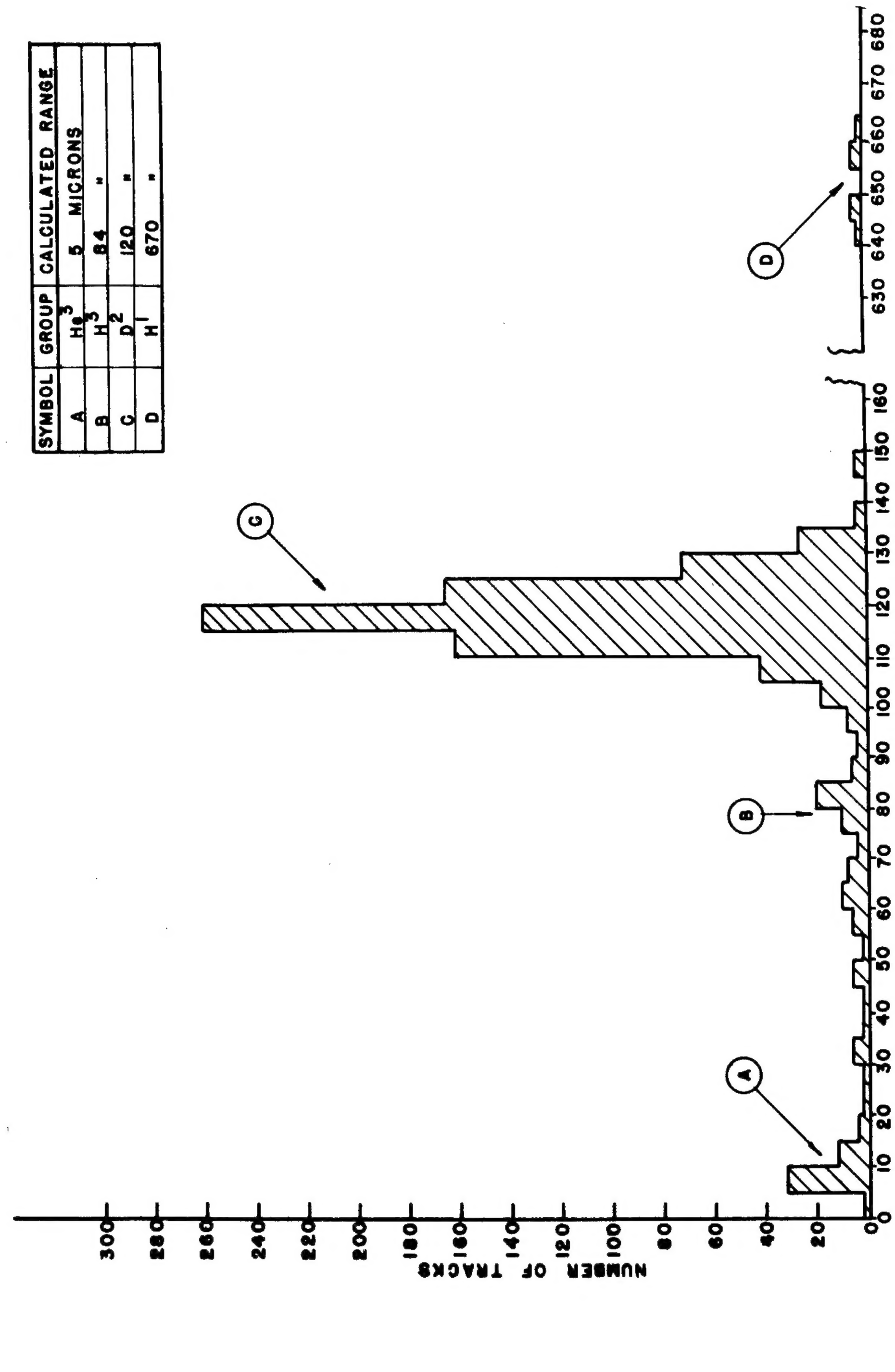

SYMBOL | GROUP | CALCULATED RANGE
A | He3 | 5 MICRONS
B | H3 | 84 "
C | D2 | 120 "
D | H1 | 670 "
A
B
C
D
NUMBER OF TRACKS
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
RANGE IN MICRONS
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
630 640 650 660 670 680

Figure 3.

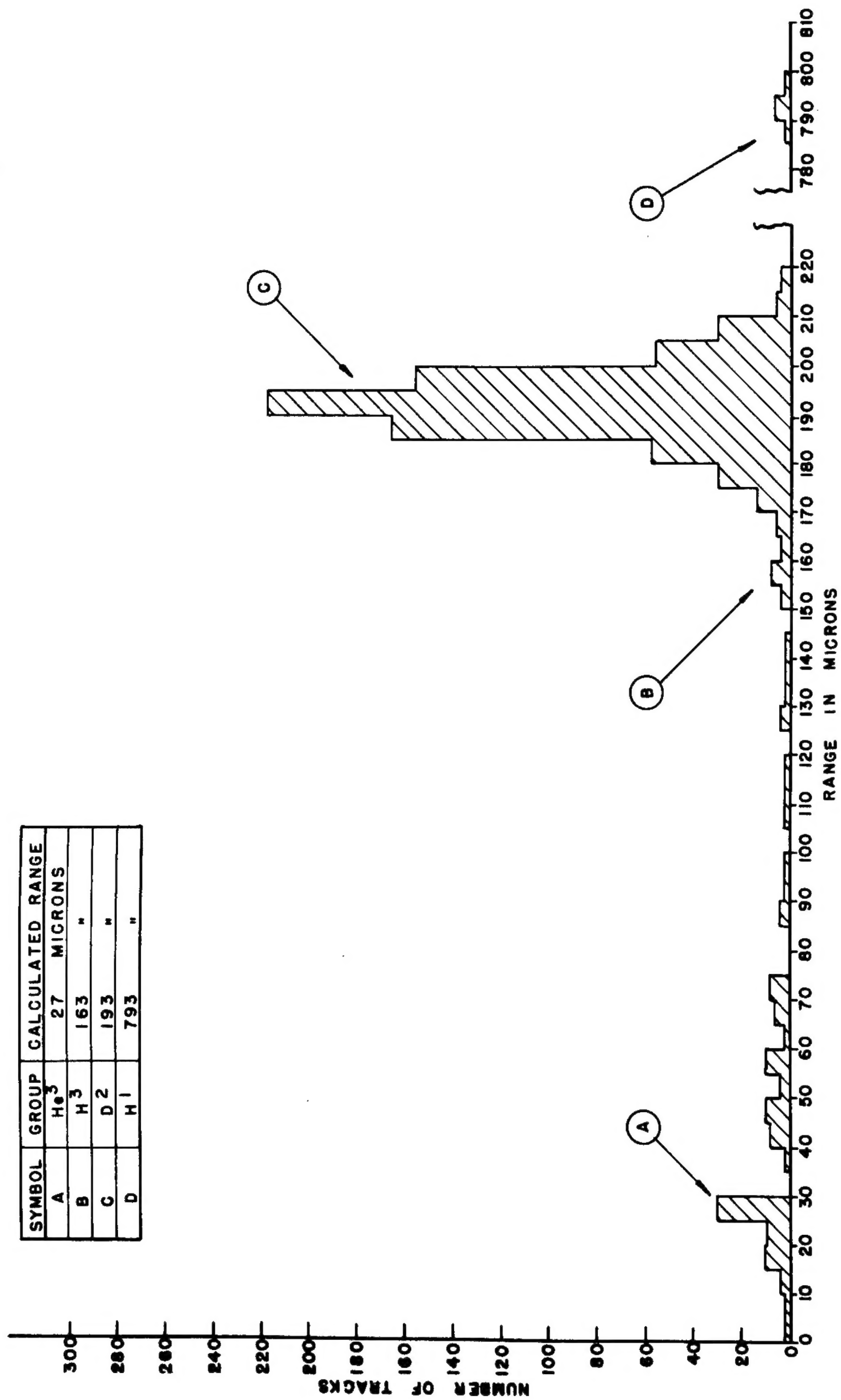

SYMBOL GROUP CALCULATED RANGE
MICRONS
A He^3 27
B H^3 163
C D^2 193
D H^1 793
A
B
C
D
NUMBER OF TRACKS
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
RANGE IN MICRONS
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 780 790 800 810

Figure 4.

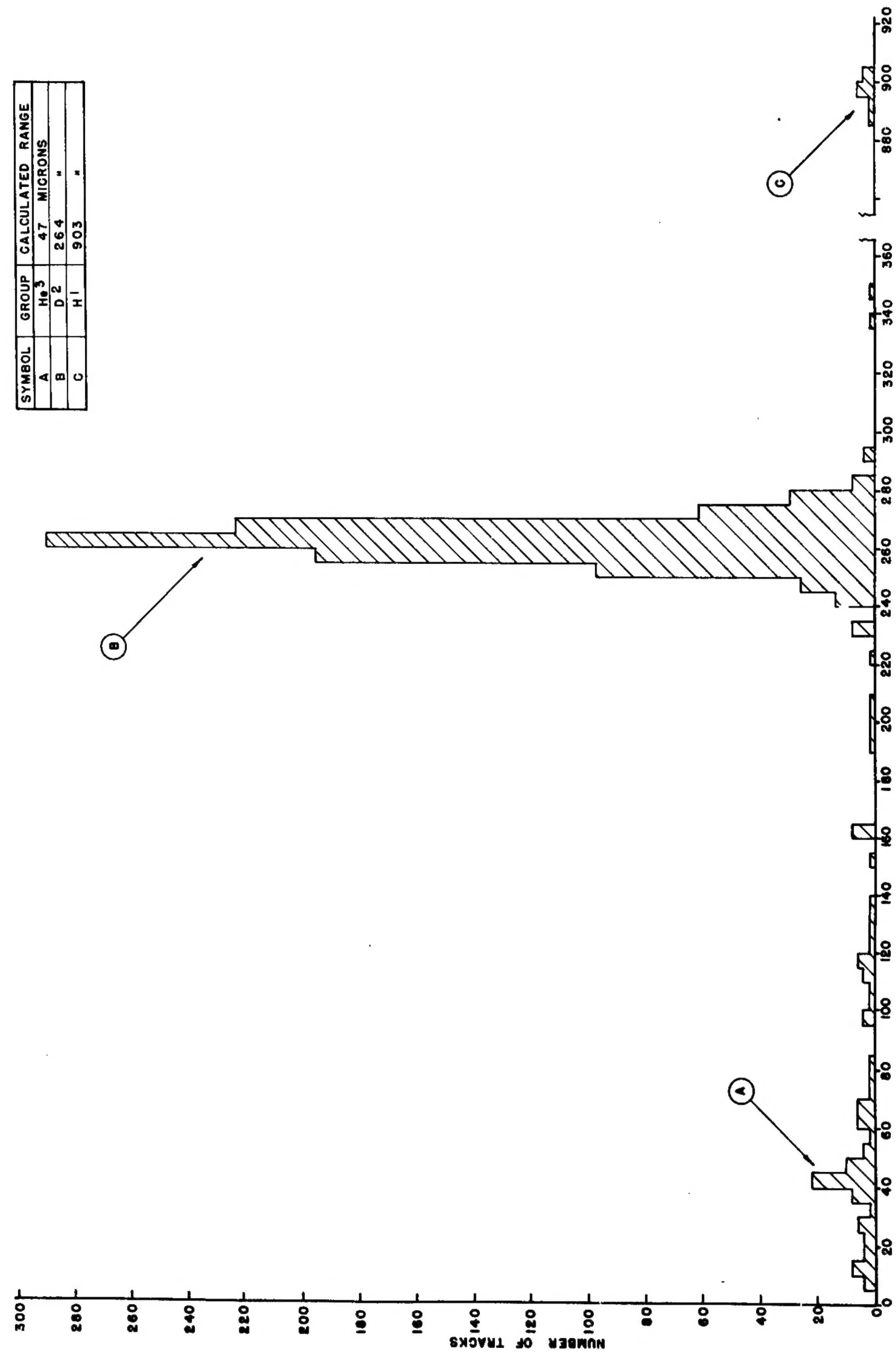

SYMBOL GROUP CALCULATED RANGE
A He3 47 MICRONS
B D2 264 "
C H1 903 "
NUMBER OF TRACKS
RANGE IN MICRONS
A
B
C

Figure 5.

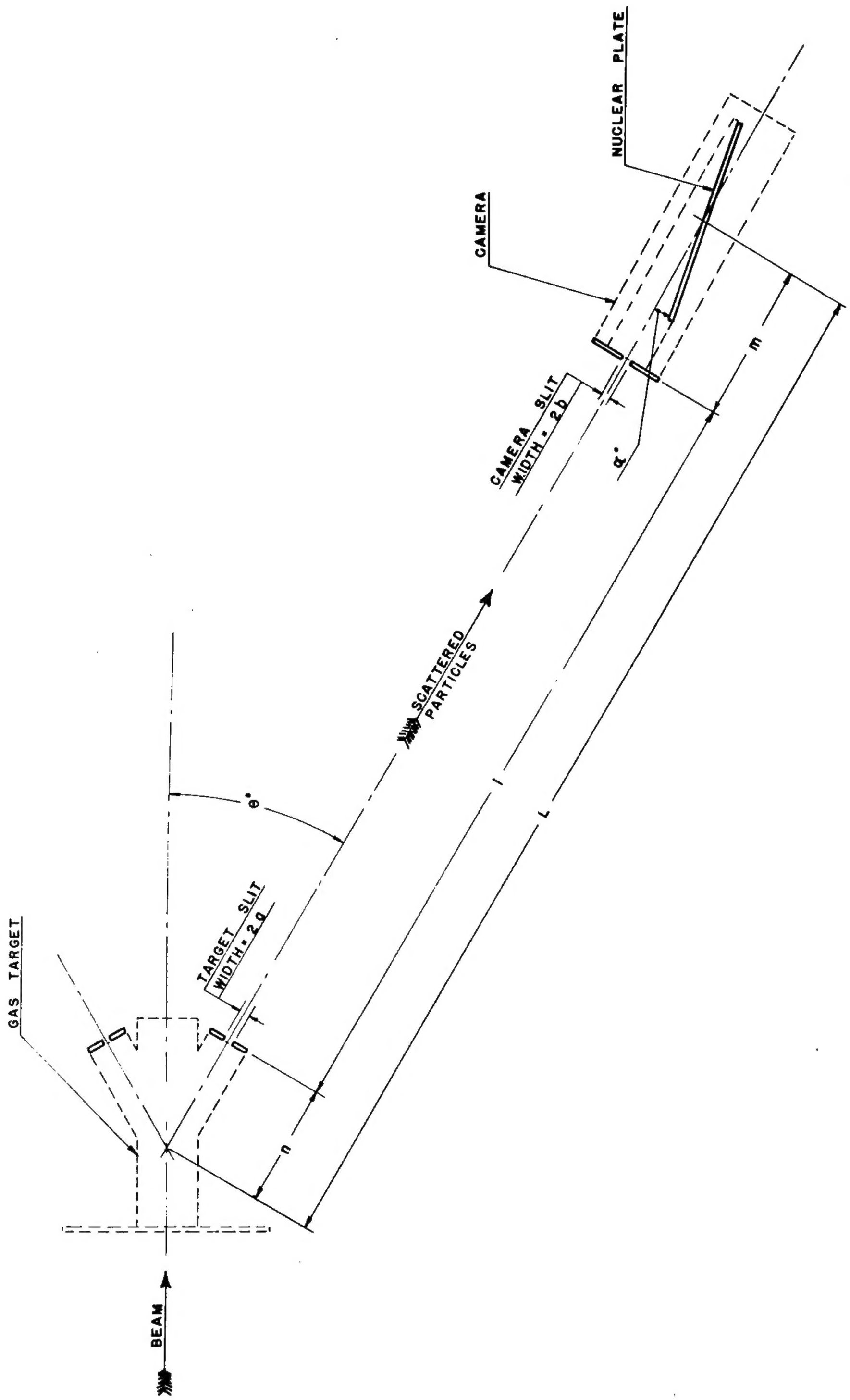

GAS TARGET
TARGET SLIT
WIDTH = 2a
θ°
SCATTERED
PARTICLES
l
L
n
m
CAMERA SLIT
WIDTH = 2b
α°
CAMERA
NUCLEAR PLATE
BEAM

Figure 6.

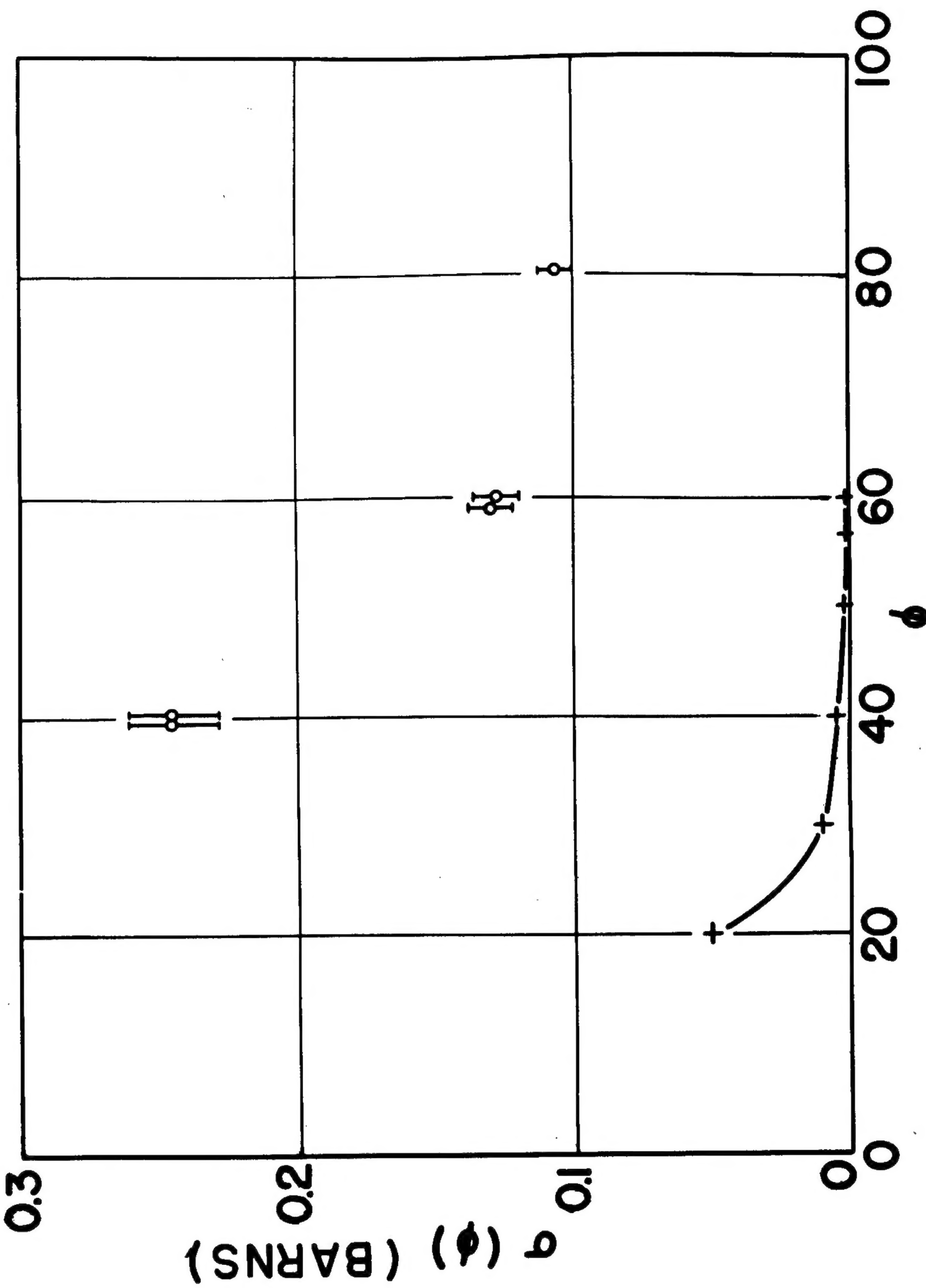


Figure 7.

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